The Benefits of Bluetooth LE Connectivity in **Power Tools**

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Introduction

In recent years, industrial tool manufacturers have started to incorporate wireless connectivity into their products to enable a wide array of features including power tool tracking, configuration updates from a smartphone app, geofencing for theft prevention, real-time performance monitoring, and over-the-air (OTA) updates. Loss prevention in particular is an important concern for many customers because it not only requires the replacement of a tool, but also reduces productivity due to unplanned downtime. Likewise, customers are also worried about the security concerns arising from counterfeits and tampering.

The addition of a Bluetooth module can help address the loss prevention concern by employing location services based on Bluetooth Received Signal Strength Indications (RSSI), Bluetooth Angle of Arrival / Angle of Departure (AoA / AoD), and the upcoming High Accuracy Distance Measurement (HADM) techniques. With the help of these ranging solutions, customers can establish geofencing and receive alert messages if the tool leaves the defined boundary. Concerns over security, on the other hand, can be addressed by selecting a wireless module that supports tamper detection, signed firmware, and secure bootloader. Power tool accountability is another emerging trend in this segment, where customers want the ability to customize tool configurations based on the user experience level and the job being performed. Finally, customers want to enable predictive maintenance in their tools to improve the product lifecycle and value. With the inclusion of a Bluetooth module and an accompanying smartphone app, manufacturers can enable users to configure tool settings from the app, making it possible to realize power tool accountability features. Additionally, periodic diagnostic reports sent from the tool, as well as running machine learning algorithms on the tool itself, can facilitate predictive maintenance.

In this whitepaper, we provide an overview of the various use cases commonly seen in the industrial power tools segment and highlight the capabilities that come with the integration of a wireless module -- specifically Bluetooth Low Energy (LE). In addition, this document highlights a couple of upcoming opportunities in this segment, namely accurate power tool tracking using Bluetooth AoA / AoD and HADM techniques, as well as predictive maintenance using machine learning.

Use Cases: Power Tools + Bluetooth LE Connectivity

Depending on the functionality and system architecture, the industrial tools market segment can be broadly classified into three use cases:

- Asset tags
- Retrofitting existing tools
- Next-generation integrated designs

Asset tag is the simplest of the three use cases, where the Bluetooth module is associated with a tool of interest. The BT module transmits status updates about the tool and enables tracking of its whereabouts. The second use case represents much of the industrial tool segment today, where wireless connectivity is being added to existing devices. Here, the wireless module operates in a Network Co-Processor (NCP) mode and enables a two-way communication between the tool and a smartphone app to implement an array of functionalities. We'll discuss these later in this document. Finally, the third use-case denotes the future trends in this market segment, where the wireless module is capable enough to handle the requirements of the application code and to enable wireless connectivity. In the following sections, each of these use cases are explained in detail.

Asset Tags

The first use case leverages the advertisement capability of the Bluetooth LE protocol to implement a tool tracking function. Figure 1 shows the system block diagram for this use case, specifically for an asset tag implementation. In this example, the device consists of a single Bluetooth LE module operating in the system-on-chip (SoC) mode, where the application code and wireless stack are executed on the host processor, and the device is transmitting beacons at regular intervals. The device is powered by a single CR2032 coin cell battery with a capacity of 235mAh. Assuming a battery derate factor of 20 percent (to account for a coin cell's non-optimal peak current handling capabilities as well as self-discharge) and a transmit interval of 1s, a system with an average current consumption of 10μA can achieve a battery life of two years. Battery life can be further improved by decreasing the transmit interval, thereby leveraging the low sleep current of the wireless MCU. For example, the battery life can exceed five years if the transmit interval is increased to four seconds.

To enable tracking capability, a device manufacturer provides a smartphone app, which has the following features:

- Periodically update the last known location of the tag using the beacons and the GPS location of the smartphone
- Allow users to log the service record of the tool that the tag is associated with
- Display tool status such as "available", "in-use", "currently being serviced", and "lost", etc.
- Monitor battery life of the coin cell battery

Table 1 shows example specifications for the asset tag use case. In this example, the default and maximum transmit power supported by the device are 0dBm and +4dBm, respectively. While most devices use a fixed transmission interval, which is preconfigured by the manufacturer, some devices might allow the user to configure the transmission interval from the smartphone app.

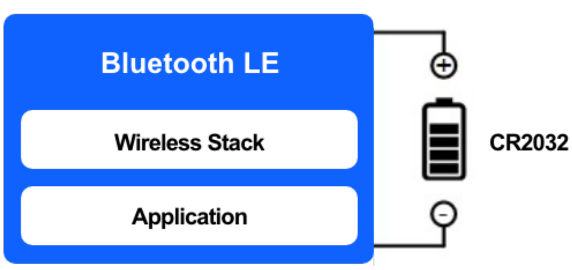


Figure1: Block Diagram of an Asset Tag

Wireless Protocol	Bluetooth LE 4.0 or newer
Transmit Power	0dBm (Typ.) +4dBm (Max)
Signal Range	100ft (30m)
Transmit Interval	1s
Power Supply	Coin Cell Battery 3V CR2032
Battery Type	Lithium
Battery Capacity	235mAh
Battery Life	1 – 2 years
Operating Temperature	-4°F to 120°F (-20°C to 50°C)
Functionality	Tracking
Certification	FCC, CE

Table 1: Typical Specifications for Use Case 1

Retrofitting Existing Tools with Bluetooth LE Connectivity

In the second use case, the Bluetooth LE module operates in an NCP mode and is used to enable wireless connectivity in industrial tools. This system architecture is commonly seen in most of the industrial tools today since manufacturers can easily add a wireless module to their design and interface it with the tool's main processor via UART or SPI interface without redesigning the entire tool circuitry. Alternatively, the use of a dedicated host processor is also applicable in tools where the RAM, flash, general purpose input output (GPIO), and peripheral requirements of the application code cannot be met by a standalone Bluetooth LE module.

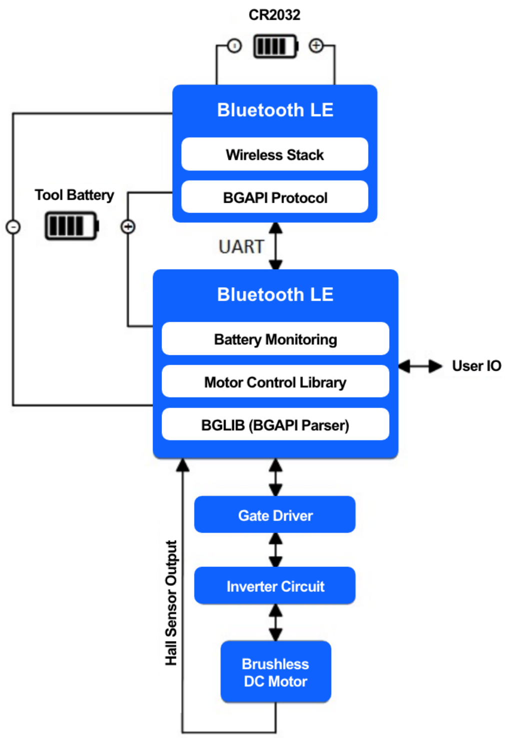


Figure2: Block diagram of a power tool where the BLE module operates in NCP mode

The following are some of the capabilities enabled by the wireless module in this use case when used with a smartphone app:

- Customize tool settings specific to a job requirement. For example, in a Bluetooth LE enabled power drill, users can select the job being performed or the type of material being handled, and the app automatically adjusts the tool settings such as the speed at the start, drive, and finish phases of the job, trigger ramp up time, kickback protection control, and other features. Alternatively, users can select the desired values and save them as custom settings on the tool.

- View inventory and get reports about a tool's performance and diagnostic messages. Users can get real-time updates about their inventory such as tool usage data, performance characteristics, and issues to proactively schedule maintenance if needed.

- Software and firmware updates to the tool. Users can schedule/perform OTA updates from the smartphone app to address software bugs, security issues, and add features.

- Industrial tool tracking capability for geofencing and theft deterrence. Users can get regular updates regarding the last known location of the tool similar to the asset tag use case. This feature allows users to get notifications if the tool leaves the defined boundary, such as a job site. The app can also have a provision to lock the tool if needed.

Figure 2 shows the system block diagram for this second use case, such as a Bluetooth LE-enabled power drill. The Bluetooth LE module supports two power source options: the primary tool battery and a CR2032 coin cell battery. In the presence of a tool battery, the wireless module supports all the functionalities mentioned earlier. If the tool battery is discharged or removed, however, the wireless module continues to be powered by the coin cell battery, but functionality in this case is restricted to beaconing for tool tracking. Since the wireless module operates in NCP mode, the wireless stack runs on the Bluetooth LE module while the application code runs on a host processor. Software components, such as the BGAPI protocol provided by Silicon Labs, can be used to simplify the communication between the application host and the Bluetooth LE NCP via UART interface.

Table 2 shows example specifications for this use case. The connection parameters between the Bluetooth LE module in the tool and the smartphone app are assigned at the time of tool registration. The transmit power of the wireless module is typically set at 0dBm with a maximum of +8dBm. Connection interval between the tool and the app can range from 100ms to 4s, depending on the target application. For example, if the wireless connection is primarily used for updating tool configurations and reading diagnostic messages, a connection interval of 4s will suffice. Alternatively, to allow users to monitor the performance of the tool in real time and to perform predictive maintenance, a shorter connection interval may be required. The smartphone app and the application code on the tool can be designed such that the connection parameter is varied dynamically depending on the target application, without the need for user involvement. Finally, battery life of the CR2032 lithium coin cell is rated for 1 to 2 years, depending on the transmit power and interval.

Wireless Protocol	Bluetooth LE 4.0 or newer
Transmit Power	0dBm (Typ.) +4dBm (Max if powered by CR2032) +8dBm (Max if powered by tool battery) +4dBm (Max)
Signal Range	100ft (30m)
Transmit Interval	100ms – 4s
Power Supply	Tool Battery (18v – 21v battery pack) Coin Cell Battery 3V CR2032
Battery Type	Tool battery: Lithium Ion Coin cell: Lithium
Battery Capacity	Tool battery: 3 – 8Ah Coin cell: 235mAh
Battery Life	Tool battery: Varies based on usage Coin cell: 1 – 2 years
Operating Temperature	-4°F to 120°F (-20°C to 50°C)
Functionality	Configuration Updates Performance Monitoring Tracking
Certification	FCC, CE

Table 2: Typical Specification of Use Case 2

Next-Generation Integrated Designs

In the third use case, the Bluetooth LE module operates in SoC mode where the application code and wireless stack are executed on the module itself. This results in a more integrated design for the tool, resulting in bill of material (BOM) cost reduction and improvements in battery life in some products and configurations. This system architecture will start becoming prevalent in newer tool designs as significant improvements are currently being made in wireless MCUs with the addition of more memory, processing speed, analog/digital peripherals, and dedicated hardware blocks to accelerate machine learning operations.

Figure 3 shows the block diagram for this use case, specifically a Bluetooth LE-enabled tool battery with the example specifications shown in Table 3. In this implementation, the wireless MCU application code is responsible for the battery management system and providing a Bluetooth connection with the smartphone app. The battery management system is critical in lithium-ion batteries because the charge capacity of the individual batteries is affected by aging, manufacturing process variation, and temperature. Thus, the battery management system requires monitoring of the temperature, current, voltage, and charging/discharging characteristics of individual batteries in the battery pack using an external cell monitoring/balancing circuit. The cell balancing circuit may be active or passive and is used to optimize the charging and discharging cycles of the individual batteries, thereby prolonging the lifetime of the battery pack. The following are some of the capabilities enabled by the Bluetooth LE module in conjunction with the smartphone app:

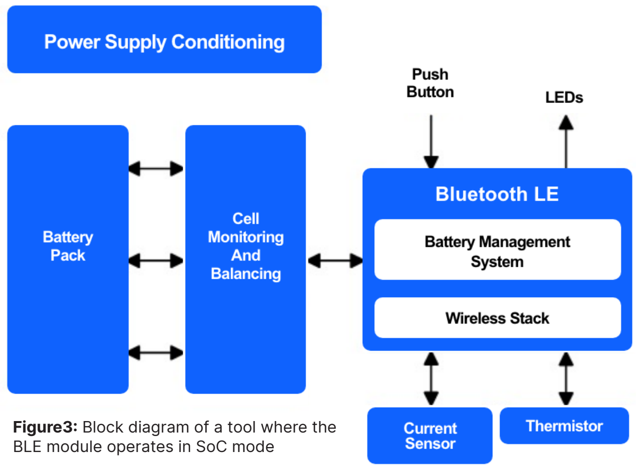


Figure3: Block diagram of a tool where the BLE module operates in SoC mode

- Monitor the battery characteristics using voltage, current, temperature sensors, and a cell monitoring/balancing circuit
- Periodically update the user about the battery performance characteristics such as remaining battery life, battery health, and temperature
- Keep track of the location and time where the battery was last seen based on the periodic Bluetooth connections
- During charging, provide updates about the state of battery charge (low battery, charging complete, etc.), whether the battery is within the connection range of the smartphone, and alerts for overheating issues.
- Help users to locate the battery while in its vicinity by enabling the LEDs on the battery to blink
- Lock or unlock the battery in the event it is lost or if it is out of range from the smartphone
- Perform OTA update for bug fixes, security improvements, and firmware upgrades

Wireless Protocol	Bluetooth LE 4.0 or newer
Transmit Power	0dBm (Typ.) +4dBm (Max if powered by CR2032) +8dBm (Max if powered by tool battery)
Signal Range	100ft (30m)
Transmit Interval	100ms – 4s
Power Supply	Tool Battery (18v – 21v battery pack)
Battery Type	Lithium Ion
Battery Capacity	3 – 8Ah
Battery Life	Varies based on usage
Operating Temperature	-4°F to 120°F (-20°C to 50°C)
Functionality	Configuration Updates Performance monitoring Battery management system Motor control Tool Tracking
Certification	FCC, CE

Table 3: Typical Specifications for Use Case 3

Opportunities

Power Tool Tracking using Bluetooth AoA/AoD and HADM

Power tool tracking is one of the common issues faced by users in a construction site, factory, warehouse, or garage setting. To address this issue, manufacturers currently offer a ranging solution that uses the signal strength of the received Bluetooth packet to estimate the device position. In a wireless communication, signal strength is theoretically reduced as a function of the square of the distance between the transmitting and receiving devices. Therefore, by leveraging the received signal strength values and using some sophisticated signal processing algorithms, it is possible to estimate the distance between the two devices. While this solution is relatively simple to implement, its accuracy is largely dependent on wireless channel conditions. As a result, real world accuracy of this solution is typically limited to 5 to 10m radius, which may not suffice for the various use cases described above. To address this issue, Bluetooth offers two direction finding solutions: Angle of Arrival/Departure (AoA/AoD) and High Accuracy Distance Measurement (HADM).

As the name suggests, the AoA technique estimates the direction from which the RF signal is received, using an antenna array at the receiver to facilitate the measurement. A system incorporating three or more of these multi-antenna receivers can perform triangulation by leveraging the angle measurements and known location of the receivers to accurately estimate the position of a Bluetooth tag, as shown in Figure 4. HADM, on the other hand, is a new direction-finding technology in Bluetooth, which uses time-of-flight or phase-based measurements to estimate the distance between the transmitting and receiving devices. Thereby, a system consisting of three or more receivers can perform trilateration as shown in Figure 4, where the distance measurements from multiple receivers can be leveraged to estimate the tag position. Unlike AoA, which requires an antenna array at the receiver, HADM typically only requires a single antenna solution. However, in the presence of significant channel impediments (such as multi-path and fading), a multiple antenna HADM solution can have significantly improved accuracy. To facilitate the use of multiple antennas, the Bluetooth specification supports up to four antenna paths when measuring the distance, which can result in a 1×4 or 2×2 antenna configuration on the transmitter receiver nodes.

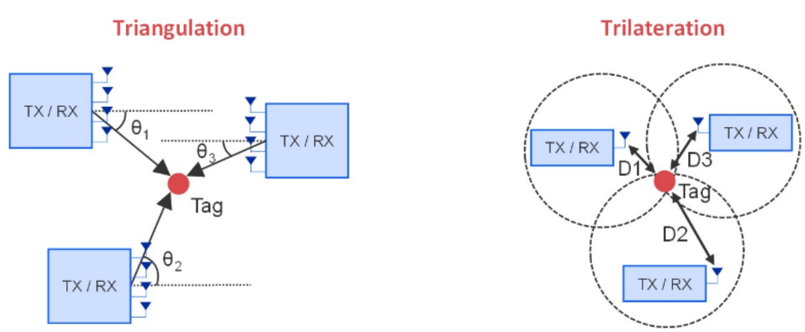


Figure 4: Triangulation and Trilateration techniques

Enabling tool tracking using AoA will require the antenna array to be mounted on the ceiling of a factory or construction site. These arrays can be a part of existing infrastructure (such as the access points) and can currently track up to 500 tools in real time. Alternatively, a simple, single-receiver HADM-based tool tracker, can provide the user with information about how far away the tool is, without providing much information about directionality. By combining the AoA and HADM techniques, however, users can determine the precise location of the tool with just a single receiver. For example, a handheld tool tracker supporting both AoA and HADM can combine the azimuth and elevation angles provided by AoA with the distance parameter returned by HADM to precisely indicate in which direction the tool is located along with a depth field. This approach allows a tool tracking solution to achieve sub-meter level accuracy, thereby significantly improving the user experience in the scenarios listed above.

Predictive Maintenance

Tool maintenance is an important topic in the industrial tools segment. Most users currently schedule maintenance at regular intervals or upon encountering a problem. Adding predictive maintenance capabilities to the tool can allow the user to schedule maintenance based on usage characteristics, thereby the saving cost of periodic maintenance while ensuring the tools are serviced when needed. Figure 5 shows two different predictive maintenance system architectures that can be realized by integrating wireless capability into industrial tools.

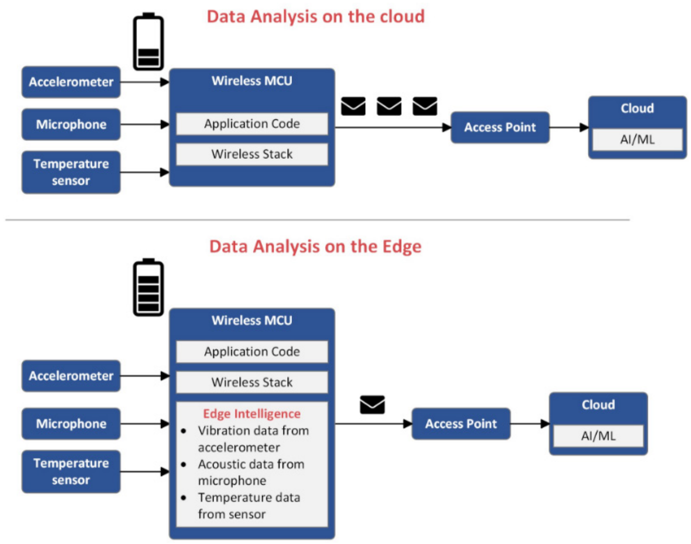
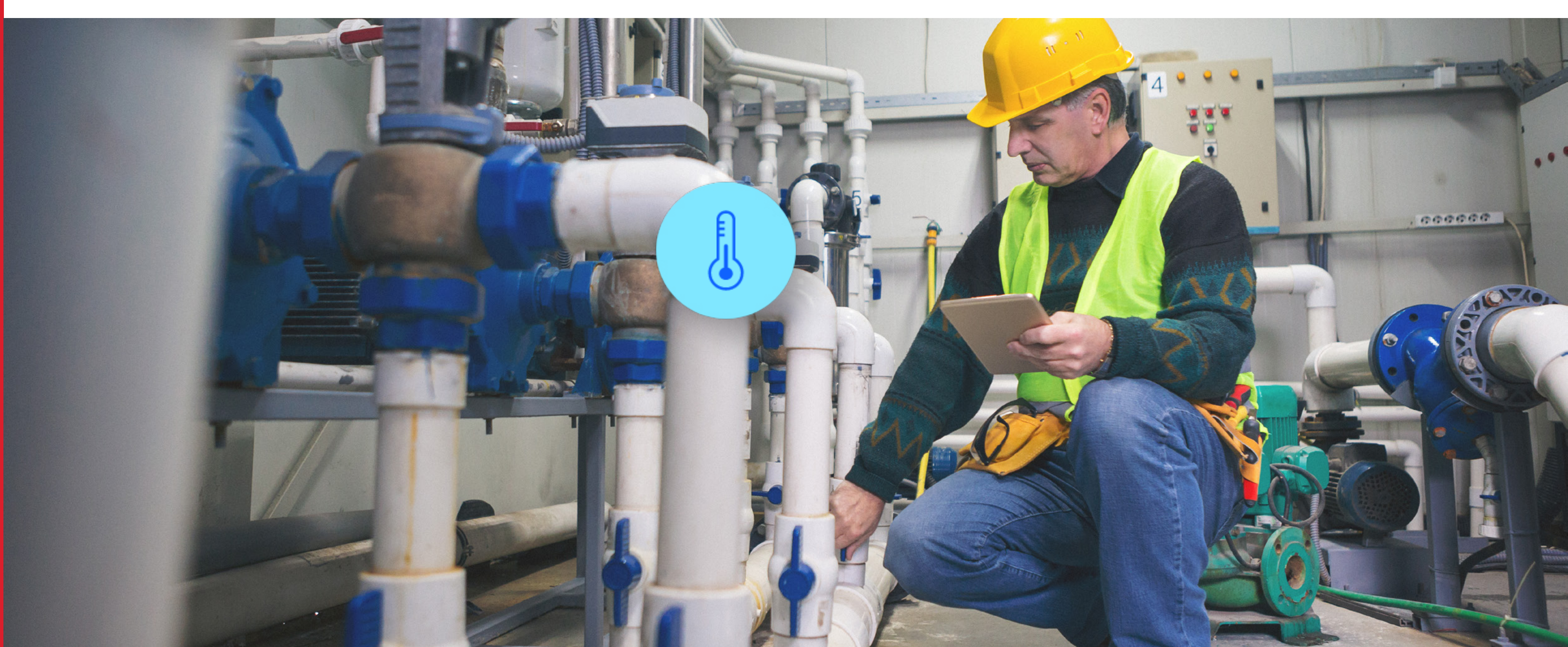


Figure 5: Predictive Maintenance in Industrial Tools Sement

In the first cloud-based architecture, the wireless module is used to periodically upload various sensor data characterizing the tool performance to the cloud via a gateway. Thereby, users can run sophisticated signal processing and machine learning algorithms on the sensor data to predict when to schedule the next tool service. While this approach is beneficial to study the aging aspects of the tools and associated performance degradations, capturing intermittent faults and system problems that may arise thereafter will require the tool to transmit the data at more frequent intervals, negatively affecting its battery life. Tool manufacturers can increase the battery capacity to overcome this limitation, but it comes at a higher BOM cost and larger product size. The second edge-based system architecture shown in Figure 5 addresses this issue, allowing edge intelligence implemented on the embedded MCU to monitor tool performance between transmission intervals. The embedded machine learning model can be trained to detect faults that occur during run time by analyzing vibration, acoustic, and temperature data, and can transmit alert messages if it identifies any anomaly in the measured data. The model can be trained to detect specific patterns in the data to identify faults of interest or can be modelled against the ideal performance characteristics of the tool to detect any deviation in the performance. Since the model is executed on an embedded platform, its performance capabilities are expected to be limited compared with a cloud-based analysis. However, since this architecture aims to reduce the data transmission frequency to improve battery life, employing a scaled model with prediction accuracies greater than 95 percent will suffice for the use cases mentioned earlier. Additionally, recent improvements in embedded hardware that accelerate machine learning operations, and the availability of necessary software and tool support for such implementation, make it easier for manufacturers to integrate this feature into their products.



Conclusion

In summary, the addition of wireless capability to traditional industrial power tools provides several benefits: tool configurability based on job requirements, highly accurate tool tracking, real-time performance monitoring, OTA updates for software and firmware changes, and many more. To this end, Silicon Labs provides a great range of products for cost-effective implementation of such solutions. Our products can be purchased as pre-certified SiP or PCB modules with integrated antenna to reduce development time and cost. With the lowest active and sleep currents compared to other products available in the market today, our wireless MCUs can significantly improve the battery life performance of industrial tools. Silicon Labs has studied the various challenges encountered when implementing an accurate tool tracking system, which involves extensive modeling, experimentation, and live tool tracking using RSSI and Bluetooth AoA techniques, while simultaneously investigating various upcoming technologies in this field. As a result, we offer extensive documentation in the form of reference designs, application notes, and sample code for customers to easily realize this technology in their products. Finally, Silicon Labs offers enhanced security options, which includes IP protection and preventing malicious tampering, both OTA and in physical proximity.